



The Guildhall, Register Square, Beverley, East Yorkshire

Alison Arnold, Robert Howard, Cathy Tyers,
Christopher Bronk Ramsey, Elaine Dunbar, and Peter Marshall

Discovery, Innovation and Science in the Historic Environment



THE GUILDHALL, REGISTER SQUARE
BEVERLEY, EAST YORKSHIRE

Tree-ring and radiocarbon analysis of oak timbers

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SUMMARY

Tree-ring analysis of samples taken from The Guildhall resulted in the construction of four site sequences: BEVJSQ01, a site sequence of 197 rings containing four samples, BEVJSQ02, an 82-ring site sequence also containing four samples, and BEVJSQ03 and BEVJSQ04, site sequences of 84 rings and 63 rings respectively each of which contained two samples. None of these, or any of the ungrouped individual series, could be securely dated using tree-ring analysis.

Tree-ring analysis did, however, identify that BEVJSQ01 cross-matched with an undated site master chronology from 15 Flemingate, BEVGSQ02, producing a combined sequence, BEVGJSQ01, of 197 rings. Two dendrochronological samples, one from BEVJSQ01 and one from BEVGSQ01, were sub-sampled for radiocarbon dating. The combined sequence, BEVGJSQ01, was subsequently dated by a combination of dendrochronology and radiocarbon analysis to the period AD 1245–1441_{DR}, with BEVJSQ01 being dated to AD 1245–1441_{DR}.

The four dated timbers, three of which showed clear signs of reuse, are broadly contemporary. The two from the roof over the Magistrates' room were both probably felled in, or around, AD 1441_{DR}. One of those from the Courtroom roof was also probably felled in, or around, AD 1441_{DR}, whilst the other was felled slightly earlier in the range AD 1402–27_{DR}.

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INTRODUCTION

The *Early Fabric in Historic Towns: Voluntary Group Projects*, funded by Historic England, have been developed in the recognition and acknowledgement of the excellent work being undertaken by local vernacular groups in the study of local architectural trends and fabrics. The project's intention is to encourage this type of study through the provision of support and facilitate training of more people in building analysis and recording. The local projects were coordinated by Rebecca Lane (Historic England South West Region: Senior Architectural Investigator).

Early Fabric in Beverley Project

Whilst there is a corpus of research on form and age of the town of Beverley, it does not cover detailed examination of early fabric or aspects of typology, with analysis and interpretation of existing buildings until now not having benefited from dendrochronology, with the exception of some limited work on the Minster.

Initially, 13 properties were identified that were thought to be key to understanding the town's architectural development for a programme of comprehensive investigation. These properties were assessed for their suitability for tree-ring dating and those found to contain timbers potentially suitable for analysis were sampled. As the project progressed and some of the original buildings identified were rejected as unsuitable for tree-ring dating, further candidates for tree-ring analysis were assessed and sampled if appropriate.

It was hoped that successful dating of these buildings would extend the knowledge of early fabric and selected buildings in this historic town of Beverley in support of Historic England's responsibility to identify and understand the urban vernacular and historic environment of a market town. The reports produced on the buildings recorded as part of this project by the Yorkshire Vernacular Buildings Study Group, led by David Cook, will be held in the YVBSG archive and will be available through their website (www.yvbsg.org.uk), whilst a summary of the project is presented in Vernacular Architecture (Cook and Neave 2018).

BUILDING DESCRIPTION

The Grade I listed Guildhall (<https://historicengland.org.uk/listing/the-list/list-entry/1083960>) is located at the entry to Register Square, Beverley (Figs 1–3). It has an associated YVBSG archive report (YVBSG 2016) from which this description is summarised. It is aligned such that it faces east-northeast onto Register Square but for the purposes of this report it is referred to as facing east.

The Guildhall is thought to date to the fifteenth century but underwent substantial work in AD 1762–4 directed by William Middleton. The porticoed front is somewhat later again, attributed to Charles Mountain Jnr in AD 1832. There are five roof structures over this building with the earliest ones thought to be those to the rear (west end), above the Courtroom and the Magistrates' Room. These roofs are parallel to each other, running in an east to west direction, and form a single block of double pile form. They are believed to date to the AD 1762–4 phase of work.

The roof over the Magistrates' Room is of four bays (Fig 4), separated by three king-post, principal rafter trusses, with side purlins and ridges. The roof over the Courtroom is longer, consisting of six bays (Fig 4), separated by five king-post and principal rafter trusses, between which are side purlins and a ridge (Fig 5). Both roofs utilise a substantial amount of reused timber.

SAMPLING

A total of 25 samples were taken from oak (*Quercus* sp) timbers of the roofs over the Magistrates' Room and the Courtroom. Each core sample was given the code BEV-J and numbered 01–25, with samples BEV-J01–12 from the Magistrates' Room roof and BEV-J13–25 from the Courtroom roof. The location of all samples was noted at the time of sampling and has been marked on Figures 6 and 7. Further details relating to the samples can be found in Table 1. At the time of sampling it was seen that a number of the timbers displayed clear signs of reuse in the form of redundant mortices, these have been marked in Table 1, but this does not preclude other timbers from also being reused. Trusses have been numbered from east to west as per the report produced by YVBSG (2016) and nomenclature used in this report also follows that in the YVBSG (2016) report.

TREE-RING ANALYSIS AND RESULTS

Five samples, one from the roof over the Magistrates' Room and four from the roof over the Courtroom, were found to have too few rings for secure dating and so were rejected prior to measurement. The remaining 20 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. These samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in 12 samples matching to form four groups.

Firstly, at a minimum t -value of 4.8, four samples matched each other and were combined at the relevant offset positions to form BEVJSQ01, a site sequence of 197 rings (Fig 8). A further four samples also matched each other, at a minimum t -value of 4.9, to make BEVJSQ02, a site sequence of 82 rings (Fig 9). At a t -value of 11.8, two samples grouped to form BEVJSQ03 of 84 rings (Fig 10) and finally two other samples matched each other at a t -value of 6.2 and were combined to form BEVJSQ04, a site sequence of 63 rings (Fig 11). Comparison of these site sequences, and the remaining ungrouped samples, with a full range of reference chronologies for oak timbers could not identify any secure and consistent dating.

Combining the undated sequences from the Guildhall and 15 Flemingate

Analysis of all the tree-ring data obtained as part of the Early Fabric in Beverley Project subsequently revealed that BEVJSQ01 matched a site sequence from 15 Flemingate (BEVGSQ02), which lies approximately 500m southeast of The Guildhall (Fig 12), at the very high level of similarity ($t = 9.7$). A further combined sequence, BEVGJSQ01, of 197 rings, containing the components of both BEVJSQ01 and BEVGSQ02 was then constructed at the relevant offset positions (Fig 13). This combined sequence cross-dated consistently with the reference material at a first measured ring date of AD 1245 and a last-measured ring date of

AD 1441. The evidence for this is given in Table 2 but as can be seen the levels of similarity with the reference chronologies were, combined with the geographical spread, considered insufficient to allow secure dating of this combined sequence by dendrochronology alone.

RADIOCARBON WIGGLE-MATCHING

Following the tree-ring analysis, the dating of the combined sequence comprising six samples from two sites in Beverley, BEVGJSQ01, remained uncertain. Thus single year tree-rings were sampled from timbers BEV-J04 (The Guildhall) and BEV-G04 (15 Flemingate) (Table 3). These samples were selected on the basis of the secure cross-matching between the two site sequences and hence the tentative tree-ring dates identified for the final rings of the undated individual site sequences: AD 1441 (BEVJSQ01) and AD 1431 (BEVGSQ02). The samples selected for radiocarbon dating, both thought to represent the growth-ring for AD 1419, were deliberately chosen from a steep part of the calibration curve where the radiocarbon content of the atmosphere was rapidly changing (Fig 14).

Radiocarbon dating is based on the radioactive decay of carbon-14 and can be used to date organic materials, including wood. A small proportion of the carbon atoms in the atmosphere are of a radioactive form, carbon-14. Living plants and animals take up carbon from the environment, and therefore contain a constant proportion of carbon-14. Once a plant or animal dies, however, its carbon-14 decays at a known rate. This makes it possible to calculate the date of formerly living material from the concentration of carbon-14 atoms remaining. Radiocarbon measurements, like those in Table 3 are expressed in radiocarbon years BP.

Laboratory methods

Single-year tree-ring samples were submitted to the Oxford Radiocarbon Accelerator Unit (ORAU) and Scottish Universities Environmental Research Centre (SUERC) for Accelerator Mass Spectrometry (AMS) dating. The sample submitted to the Oxford University Radiocarbon Accelerator Unit was pretreated using the acid-base-acid protocol followed by bleaching with sodium chlorite (Brock *et al* 2010, Table 1 (UW)). It was combusted and graphitised as described by Brock *et al* (2010, 110) and Dee and Bronk Ramsey (2000) and dated by AMS (Bronk Ramsey *et al* 2004). The sample submitted to SUERC was converted to α -cellulose, combusted, graphitised, and dated by AMS as described by Dunbar *et al* (2016).

Both facilities maintain continual programmes of quality assurance procedures in addition to participation in international inter-comparison exercises (Scott *et al* 2010). The two results are statistically consistent (Table 3) and a weighted mean has been taken of them before calibration. This demonstrates the reproducibility and accuracy of these measurements.

Calibration

Calibration is an essential step in using radiocarbon measurements to estimate the calendar date of samples. It is necessary because the production rate of radiocarbon in the atmosphere is not constant, but varies through time. This means that we

need to convert the radiocarbon measurement of a sample to the calendar scale using a calibration curve made up of radiocarbon ages on samples of known calendar date.

That independent scale is the IntCal13 calibration curve (Reimer *et al* 2013) constructed from radiocarbon measurements on tree rings, plant macrofossils, speleothems, corals, and foraminifera. The calibrations which relate the radiocarbon measurements directly to the calendrical time scale have been calculated using IntCal13 and the computer program OxCal v4.2 (<https://c14.arch.ox.ac.uk/oxcal/>; Bronk Ramsey 2009).

Bayesian wiggle-matching

Wiggle-matching uses information derived from tree-ring analysis, in combination with radiocarbon measurements to provide a revised understanding of the age of a timber; a review is given by Galimberti *et al* (2004). In this technique, the shapes of multiple radiocarbon distributions can be “matched” to the shape of the radiocarbon calibration curve. The exact interval between radiocarbon results can be derived from tree-ring analysis.

Although the technique can be done visually, Bayesian statistical analyses (including functions in the OxCal computer program) are now routinely employed. A general introduction to the Bayesian approach to interpreting archaeological data is provided by Buck *et al* (1996). The approach to wiggle-matching adopted here is described by Christen and Litton (1995).

Details of the algorithms employed in this analysis — a form of numerical integration undertaken using OxCal — are available from the on-line manual or in Bronk Ramsey (2009).

BEVJSQ01 and BEVGSQ02

The chronological model for the dating of site sequences BEVJSQ01 and BEVGSQ02 is shown in Figure 15. As the two single-ring samples formed in the same year and the measurements are statistically consistent, the radiocarbon ages can be combined before calibration by taking a weighted mean (Ward and Wilson 1978; Table 3). The model shows good agreement between the radiocarbon date and the relative number of years derived from the tree-ring analysis to the tentative tree-ring date of AD 1441 for the formation of the final ring of the combined sequence BEVJSQ01 ($A_{\text{comb}} = 72.7$; $A_n = 50.0$; $n=2$; Fig 15). The radiocarbon dating therefore supports the tentative tree-ring dating that had been identified but considered to be insufficiently statistically robust (Table 2).

INTERPRETATION

Four of the samples from this building have now been securely dated (Table 1; Fig 13) using a combination of dendrochronology and radiocarbon analysis. Such dates are distinguished from a date derived from ring-width dendrochronology alone by the subscript _{DR}.

Sample BEV-J04, taken from the roof over the Magistrates' Room, has complete sapwood and the last-measured ring date of AD 1441_{DR}, the felling date of the timber represented. The other dated sample (BEV-J12) from the roof over the Magistrates' Room has retained the heartwood/sapwood boundary. This dates to AD 1420_{DR} which, using the estimate that 95% of mature oak trees in this area have between 15 and 40 sapwood rings, gives a felling date within the range AD 1435–60_{DR} for the timber represented which is consistent with this timber also having been felled in, or around, AD 1441_{DR}.

The two dated samples from the roof over the Courtroom appear to represent two separate felling events. Sample BEV-J14 has a heartwood/sapwood boundary ring date of AD 1387_{DR}, giving an estimated felling date for the timber represented within the range AD 1402–27_{DR}. Sample BEV-J13 has a heartwood/sapwood boundary ring date of AD 1421_{DR}, giving an estimated felling date for the timber represented within the range AD 1436–61_{DR}, consistent with this timber also having been felled in AD 1441_{DR}.

DISCUSSION

The dated timbers from The Guildhall represent two separate felling episodes. A tiebeam in the Courtroom roof being dated to AD 1402–27_{DR}, with a king post from the Courtroom roof and a tiebeam and purlin from the Magistrates' Room roof all thought likely to have been felled somewhat later in, or around, AD 1441_{DR}. Three of the dated timbers show clear signs of previous use, as does much of the rest of the timber within the roofs; making it very likely that although no signs of reuse were seen on the fourth timber, the purlin, that this is also reused.

Although the Guildhall itself is believed to date to the fifteenth century, these two roofs are thought to belong to the AD 1762–4 building works. The tree-ring dating has shown they utilise reused timber from the first half of the fifteenth century in their construction. It is possible that this timber was salvaged from some since demolished part of the original building, although it could equally have come from a totally unrelated structure.

Three potential same tree matches were noted amongst the timbers of The Guildhall. Samples BEV-J12 and BEV-J13, from the Magistrates' Room roof and Courtroom roof respectively, crossmatch with a $t = 12.6$. The two further pairs are all from the Magistrates' Room roof: samples BEV-J02 and BEV-J10 match each other at $t = 14.1$ and BEV-J03 and BEV-J07 match each other at $t = 11.8$. In all cases the levels of similarity are sufficiently high enough to suggest the timbers represented were cut from the same trees.

Three site sequences, representing eight timbers, from this building remain undated. In all three cases, it can be said, by looking at the relative heartwood/sapwood boundary position (Figs 9–11), that the timbers represented in each site sequence were felled at the same time, even if it is not possible to say at this point when this was or even whether the three sets of timbers relate to a single, two or three felling episodes.

It is perhaps to be expected that we have at least two, and potentially more, felling episodes represented within the timbers of the Guildhall roofs, given the substantial

amount of reused timber utilised within their construction. The possibility that the roofs comprise timbers of several different dates and/or sources may have further hampered tree-ring dating

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YVBSG 2016 *The Guildhall*, Yorkshire Vernacular Buildings Study Group rep

TABLES

Table 1: Details of tree-ring samples from The Guildhall, Beverley, Yorkshire

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD _{DR})	Last heartwood ring date (AD _{DR})	Last measured ring date (AD _{DR})
Roof over Magistrates' Room						
BEV-J01	King post, truss 1 – reused	66	01	----	----	----
BEV-J02	North principal rafter, truss 1	62	01	----	----	----
BEV-J03	South principal rafter, truss 1 - reused	62	h/s	----	----	----
BEV-J04	Tiebeam, truss 1 - reused	197	21C	1245	1420	1441
BEV-J05	King post, truss 2 - reused	46	--	----	----	----
BEV-J06	North principal rafter, truss 2 – reused	61	--	----	----	----
BEV-J07	South principal rafter, truss 2 - reused	84	h/s	----	----	----
BEV-J08	King post, truss 3 – reused	112	--	----	----	----
BEV-J09	North principal rafter, truss 3 - reused	NM	--	----	----	----
BEV-J10	South principal rafter, truss 3	48	h/s	----	----	----
BEV-J11	North strut, truss 3	50	h/s	----	----	----
BEV-J12	North purlin, truss 3-west end	150	h/s	1271	1420	1420
Roof over Courtroom						
BEV-J13	King post, truss 1 - reused	146	h/s	1276	1421	1421
BEV-J14	Tiebeam, truss 1 - reused	89	h/s	1299	1387	1387
BEV-J15	South strut, truss 1	55	06	----	----	----
BEV-J16	King post, truss 2	56	h/s	----	----	----
BEV-J17	Tiebeam, truss 2 - reused	NM	--	----	----	----
BEV-J18	South principal rafter, truss 2	74	17C	----	----	----
BEV-J19	King post, truss 3 - reused	73	h/s	----	----	----
BEV-J20	South principal rafter, truss 3	47	h/s	----	----	----
BEV-J21	North strut, truss 3	48	--	----	----	----
BEV-J22	South strut, truss 3	NM	--	----	----	----
BEV-J23	North strut, truss 4	NM	--	----	----	----
BEV-J24	King post, truss 5 – reused	63	h/s	----	----	----

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD _{DR})	Last heartwood ring date (AD _{DR})	Last measured ring date (AD _{DR})
BEV-J25	Tiebeam, truss 5 - reused	NM	--	----	----	----

NM = not measured

h/s = heartwood/sapwood boundary is the last-measured ring

C = complete sapwood retained on sample, last measured ring is the felling date

AD_{DR} = radiocarbon-supported ring-width dendrochronolog

Table 2: Results of the cross-matching of combined site sequences BEVJSQ01 and BEVGSQ02 and the reference chronologies when the first-ring date is AD 1245_{DR} and the last-measured ring date is AD 1441_{DR}

Reference chronologies	t-value	Span of chronology	Reference
Ulverscroft Priory, Charnwood Forest, Leicestershire	5.6	AD 1219–1463	Arnold <i>et al</i> 2008a
The Guildhall, Boston, Lincolnshire	5.5	AD 1244–1380	Arnold <i>et al</i> 2008b
Central Tower, York Minster, North Yorkshire	5.2	AD 1214–1462	Hillam pers comm 1997
Castle House, Buckinghamshire	5.2	AD 1272–1406	Miles <i>et al</i> 2007
Blackmore Church, Essex	5.1	AD 1266–1399	Miles <i>et al</i> 2005
Clothall Bury Farmhouse, Hertfordshire	4.8	AD 1253–1367	Arnold <i>et al</i> 2003
St Anthony's Hall, York, North Yorkshire	4.7	AD 1215–1443	Arnold and Howard 2009
Church of St James, Bristol, Somerset	4.7	AD 1209–1396	Arnold and Howard 2011
Old Vicarage, New Buckenham, Norfolk	4.7	AD 1271–1451	Tyers 2004
Gothelney Hall, Charlynch, Somerset	4.6	AD 1238–1411	Arnold <i>et al</i> 2009

Table 3: Beverley: The Guildhall and 15 Flemingate radiocarbon and stable isotope results

Laboratory number	Sample reference	Material & sample details	$\delta^{13}\text{C}_{\text{IRMS}}$ (‰)	Radiocarbon Age (BP)
OxA-33690	BEV-J04: Ring 175	<i>Quercus</i> sp. sapwood, relative year 175 of the 197 year chronology BEVJSQ01 (The Guildhall)	-25.1±0.2	450±29
SUERC-66737	Ring 165	<i>Quercus</i> sp. sapwood, relative year 165 of the 177 year chronology BEVGSQ02 (15 Flemingate)	-25.9±0.2	521±28
	Weighted mean: AD 1419	T'=3.1; v=1; T'(5%)=3.8; (Ward and Wilson 1978)		487±21

FIGURES



Figure 1: Map to show the location of Beverley (red ellipse). © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

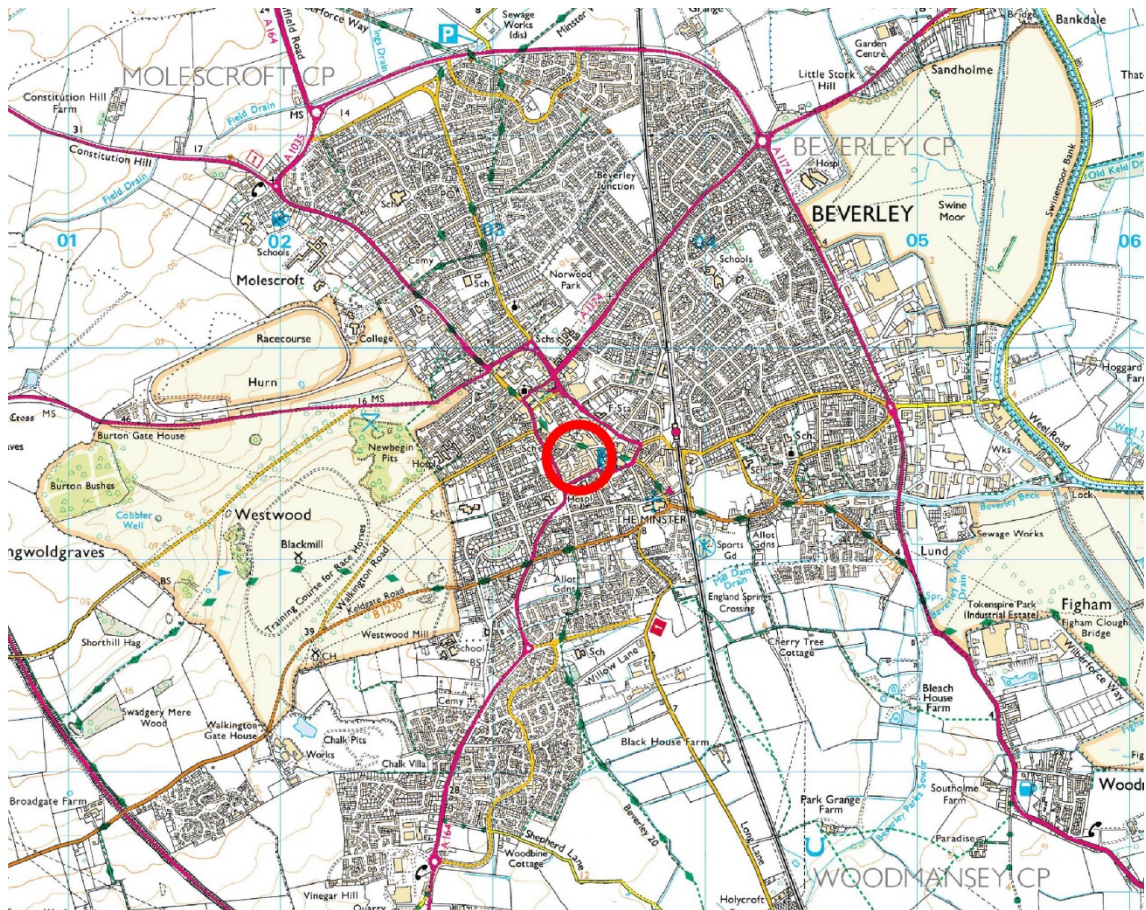


Figure 2: Map to show the general location of The Guildhall in Beverley (red ellipse). © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

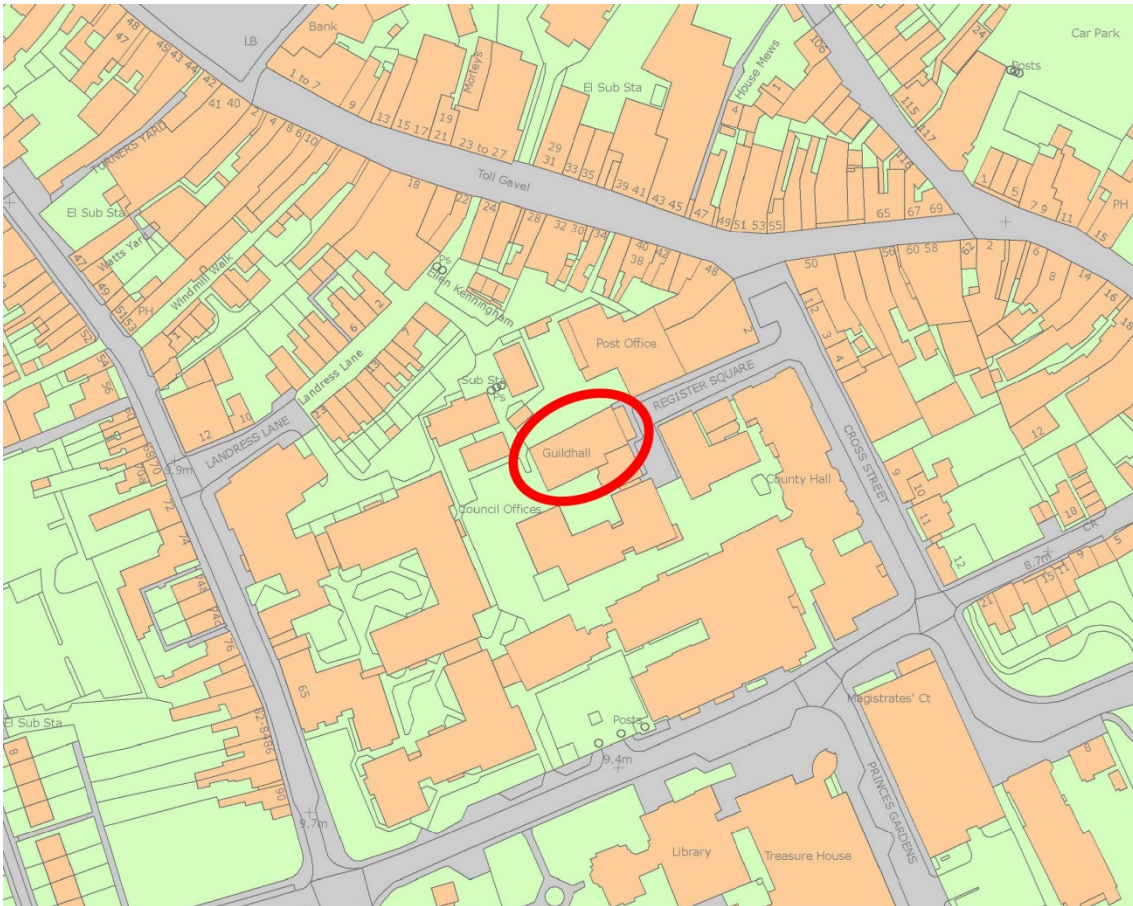


Figure 3: Map to show the precise location of The Guildhall in Beverley (red ellipse). © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

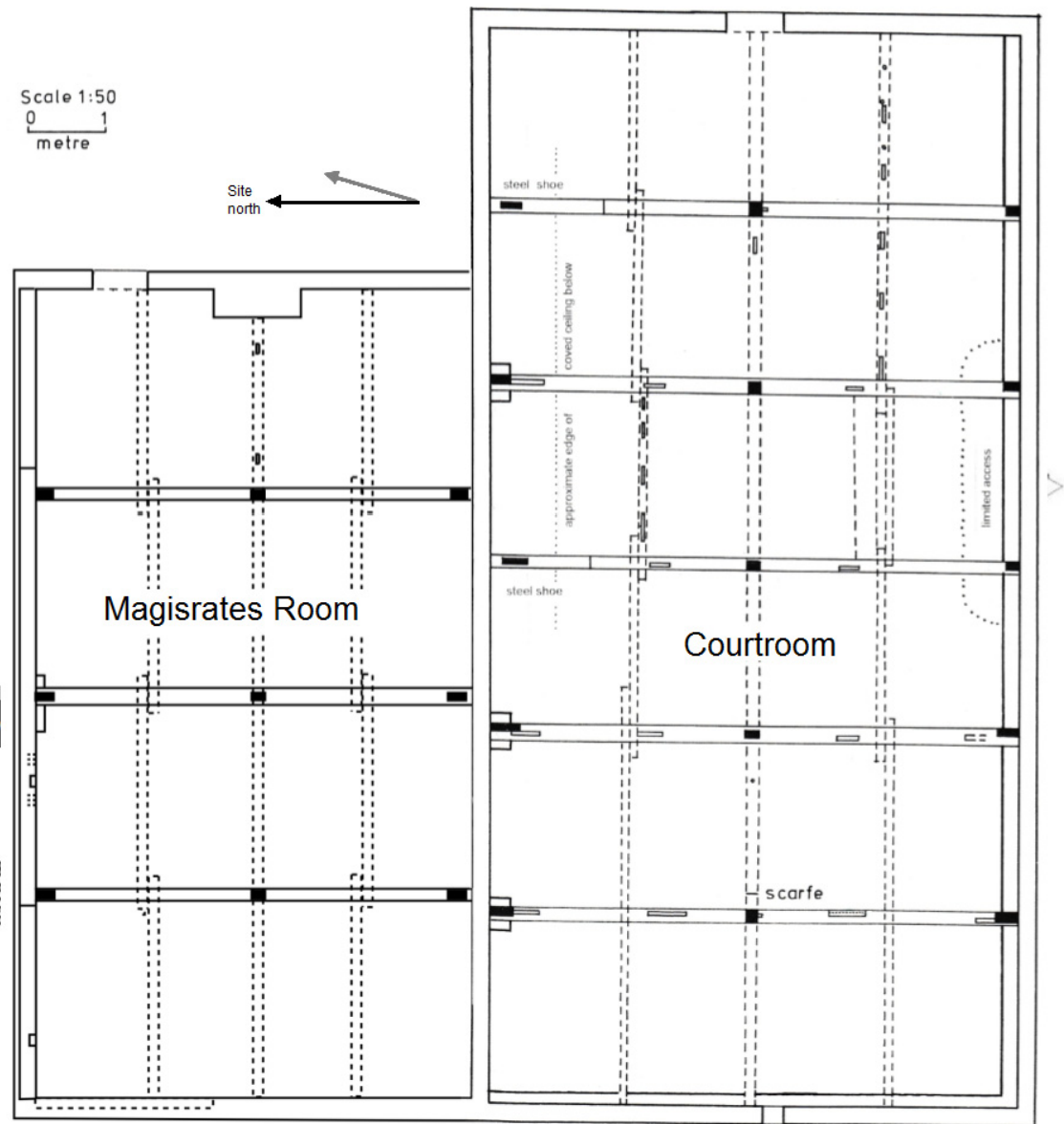


Figure 4: Plan of the Magistrates' Room and Courtroom roofs (YVBSG 2016)



Figure 5: Courtroom roof, truss 2 in foreground, photograph taken from the east (Alison Arnold)

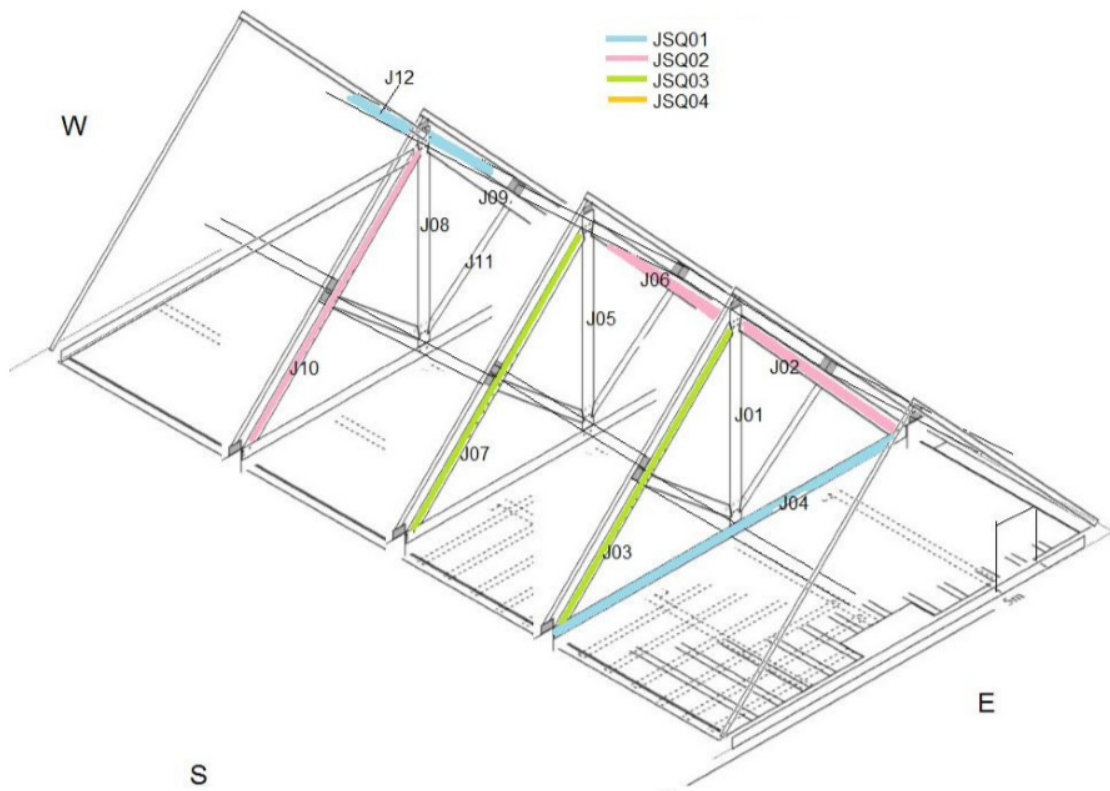


Figure 6: Magistrates' Room roof showing sampled timbers BEV-J01–12 and components of sequences (YVBSG 2016)

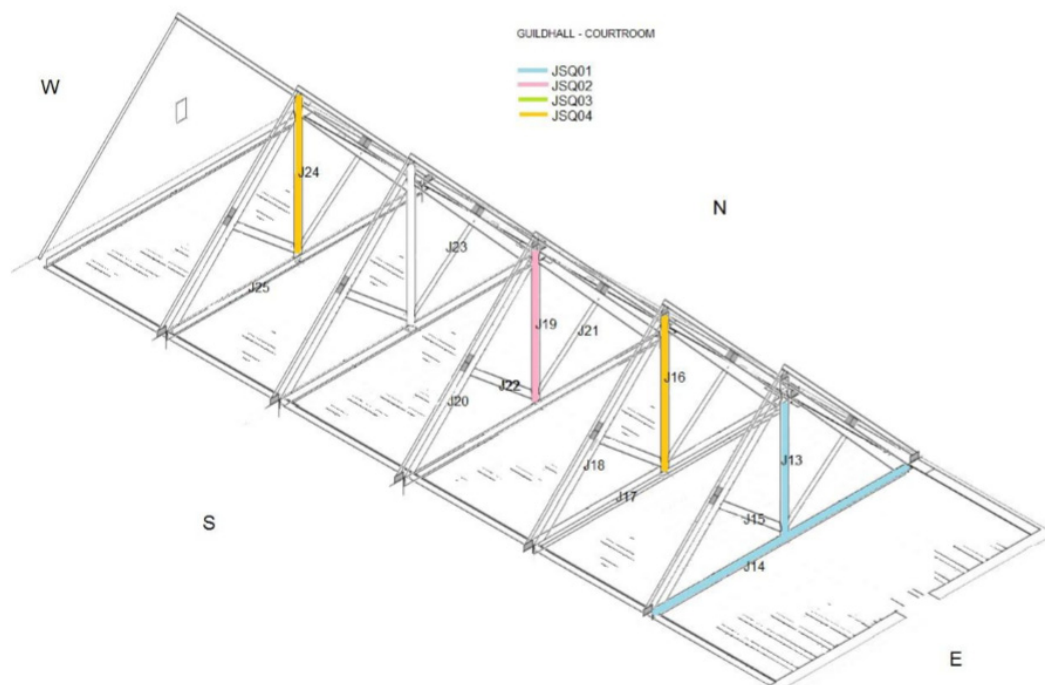


Figure 7: Magistrates' Room roof showing sampled timbers BEV-J13–25 and components of sequences (YVBSG 2016)

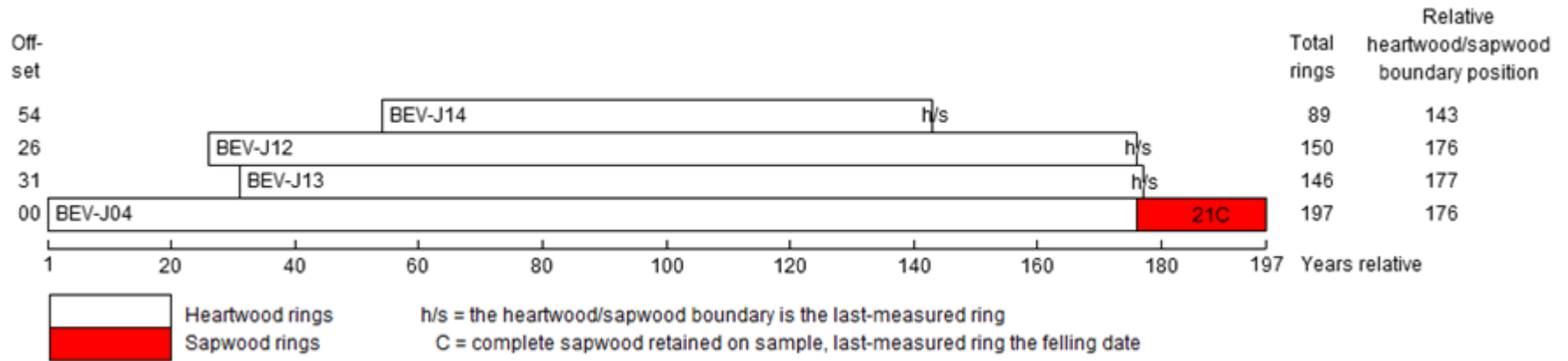


Figure 8: Bar diagram to show the relative position of samples in site sequence BEVJSQ01

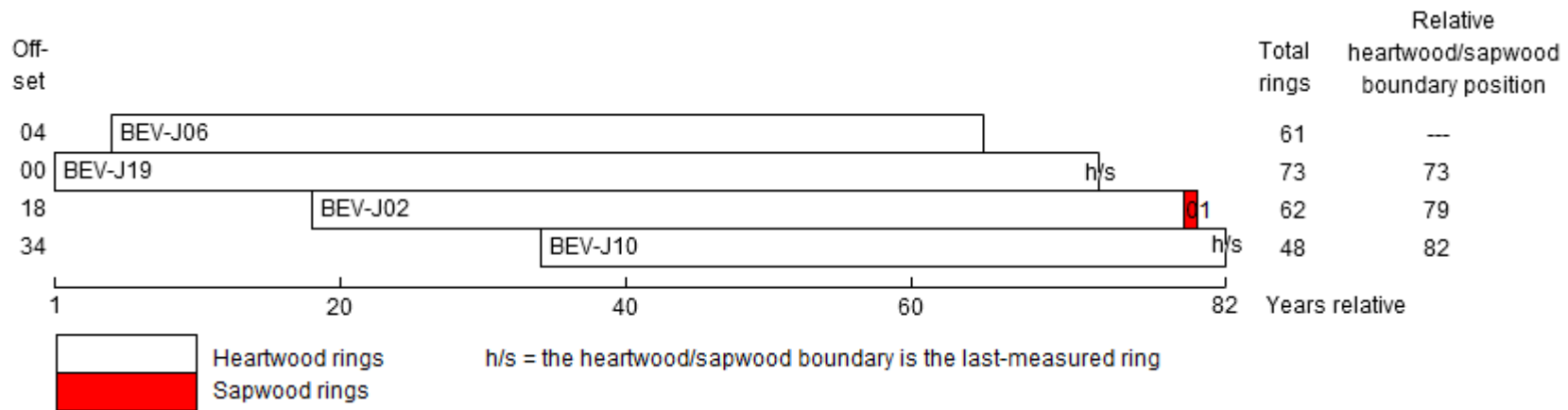


Figure 9: Bar diagram to show the relative position of samples in site sequence BEVJSQ02

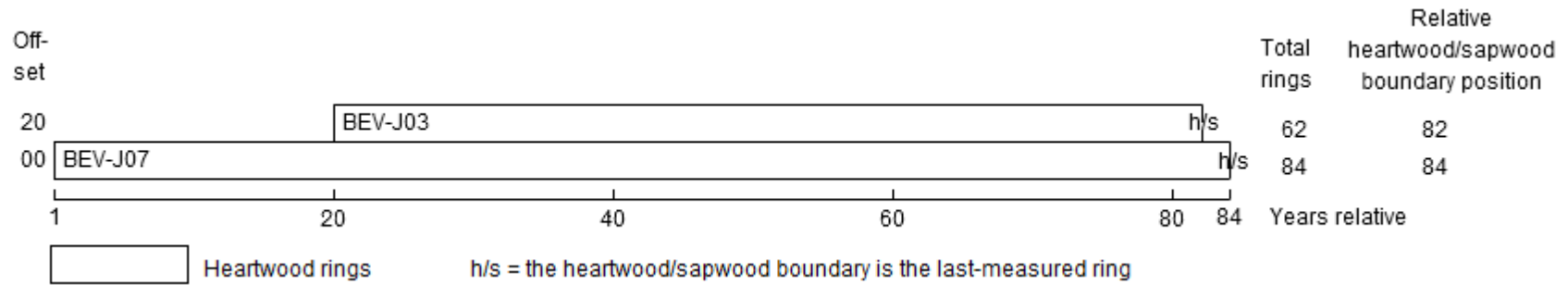


Figure 10: Bar diagram to show the relative position of samples in site sequence BEVJSQ03

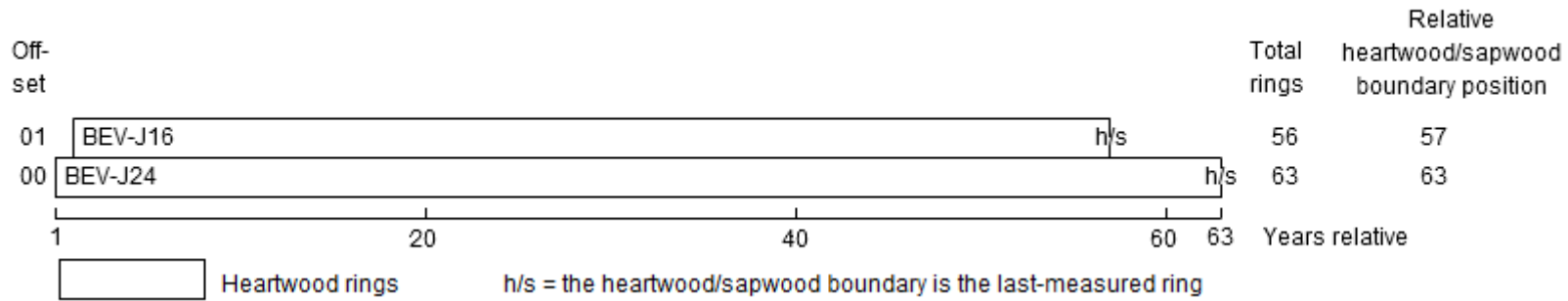


Figure 11: Bar diagram to show the relative position of samples in site sequence BEVJSQ04

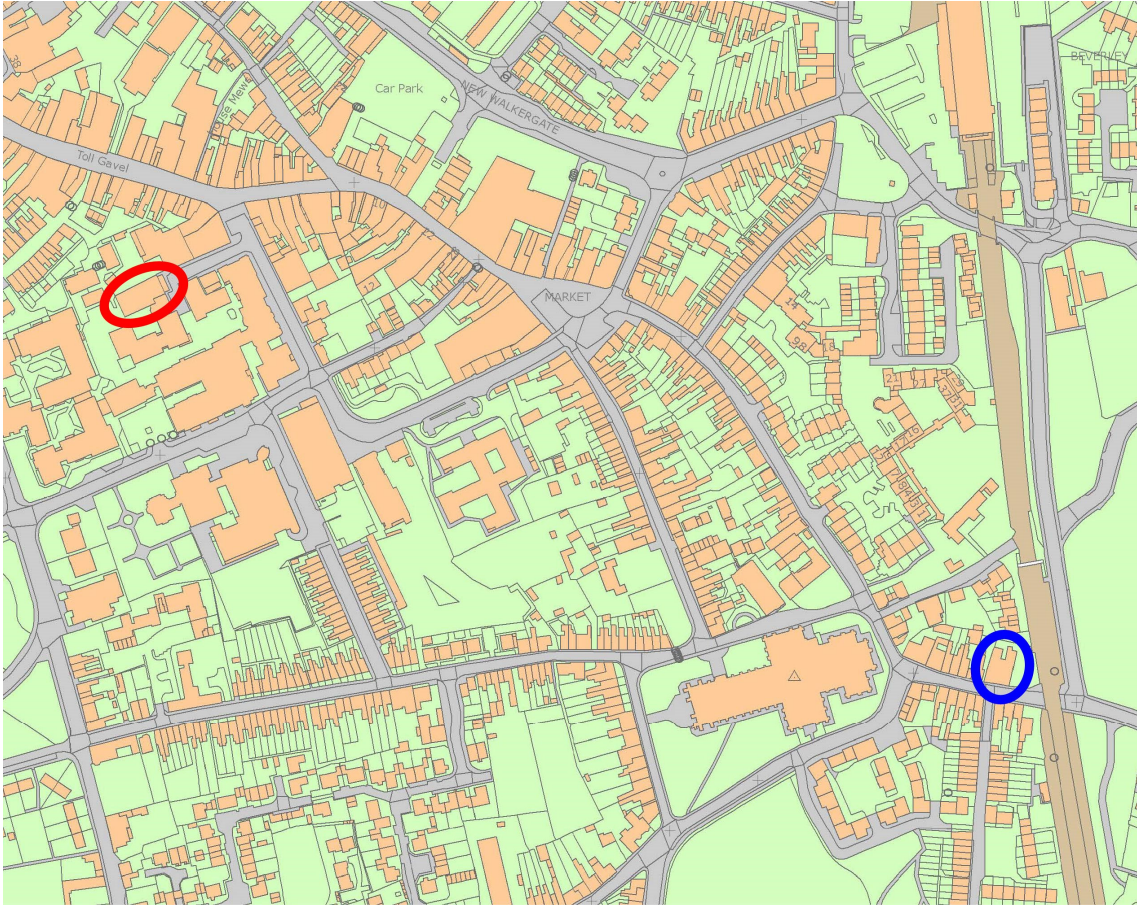


Figure 12: Map to show the proximity of 15 Flemingate (blue ellipse) to The Guildhall (red ellipse). © Crown Copyright and database right 2019. All rights reserved. Ordnance Survey Licence number 100024900

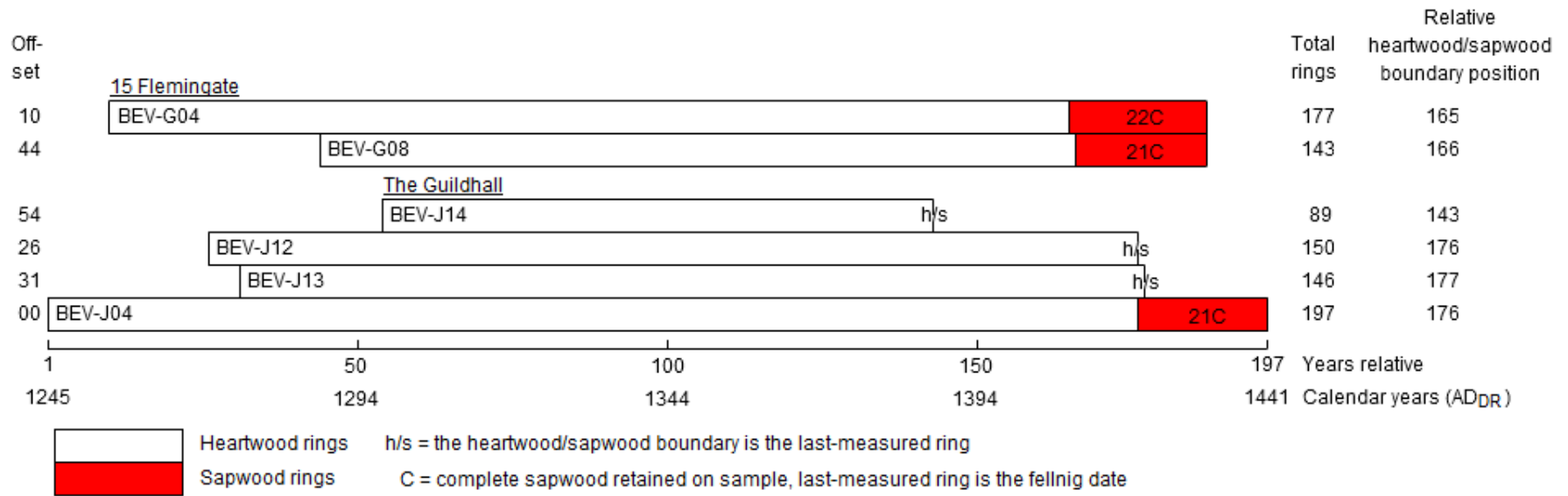


Figure 13: Bar diagram to show the relative position of samples in the combined sequence BEVGJSQ01, sorted by area

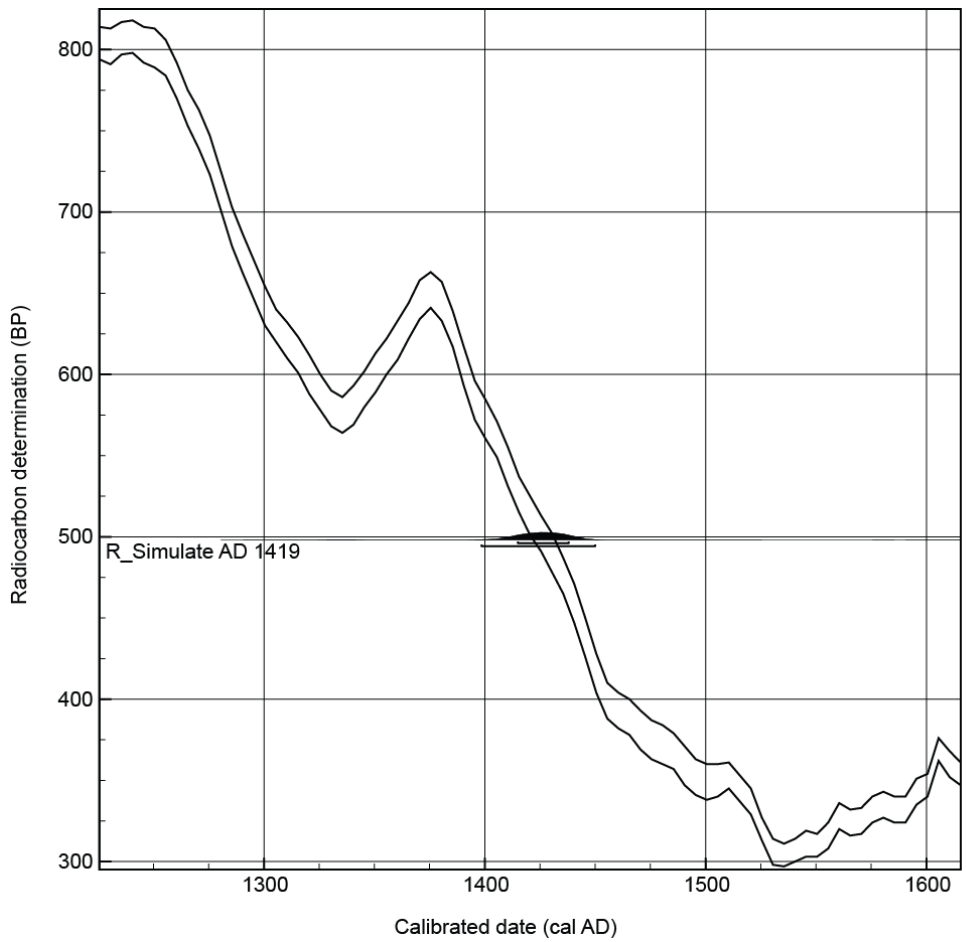


Figure 14: Probability distribution of a simulated radiocarbon date of AD 1419 plotted on the IntCal13 (Reimer et al 2013) calibration curve

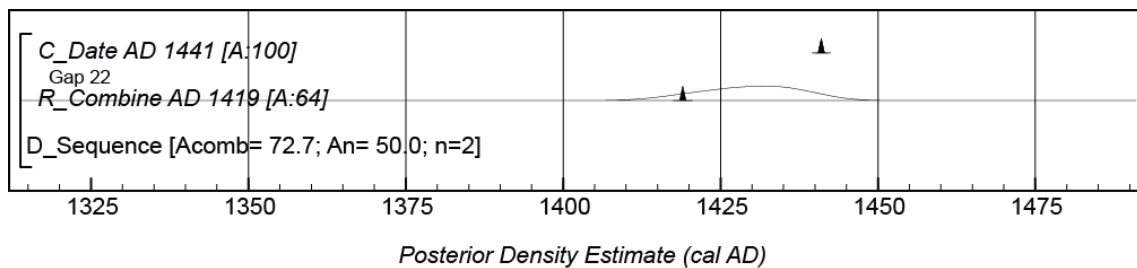


Figure 15: Probability distribution of the date of the sample with a potential tree-ring date of AD 1419 from BEVJSQ01 (ring 175) and BEVGSQ02 (ring 165). The distribution represents the relative probability that an event occurs at a particular time. For the date two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggly-match sequence incorporating the potential tree-ring date for the final ring of undated site sequence BEVJSQ01 - AD 1441. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BEV-J01A 66

214 391 329 287 241 183 383 280 287 237 213 187 183 224 192 278 235 185 210 231
321 212 240 240 261 257 251 364 480 448 362 431 265 283 202 214 216 228 193 191
257 216 185 259 205 226 133 71 88 113 158 149 159 238 204 161 113 104 213 280
215 155 191 214 236 138

BEV-J01B 66

234 392 273 289 227 184 378 257 320 251 200 201 192 229 196 265 258 201 195 242
337 215 228 259 243 240 240 374 472 453 360 392 270 247 181 223 213 223 207 197
251 207 190 256 205 239 112 76 83 108 176 129 172 249 203 183 111 102 220 272
228 151 188 209 245 138

BEV-J02A 62

266 272 251 206 253 371 267 255 163 88 151 215 286 230 195 225 169 81 85 94
200 165 162 176 95 74 111 276 364 303 241 156 160 141 132 224 266 355 253 288
208 210 238 199 202 191 184 180 193 196 203 186 188 144 162 172 149 127 105 185
140 163

BEV-J02B 62

246 253 261 204 230 392 254 264 152 89 154 213 291 226 198 220 181 93 70 106
200 162 158 177 92 81 111 276 365 315 242 155 158 135 132 232 254 350 261 300
211 217 225 205 207 183 189 199 198 205 205 187 186 146 161 173 139 121 112 191
134 165

BEV-J03A 62

320 200 159 297 268 271 401 241 293 112 285 338 375 336 325 475 270 209 295 327
334 85 55 54 78 91 189 207 183 156 161 216 207 239 251 296 257 301 288 296
94 28 46 61 67 79 71 85 101 59 119 140 61 47 65 40 54 82 63 61
50 52

BEV-J03B 62

319 196 194 267 278 295 364 245 274 97 297 334 377 316 323 479 267 216 296 334
332 82 58 54 77 95 187 207 184 157 159 198 192 248 280 284 240 292 287 294
86 33 47 48 75 75 77 84 98 67 116 140 55 48 67 40 57 75 52 69
53 49

BEV-J04A 197

223 247 261 252 197 180 168 132 112 105 133 123 93 107 129 131 113 132 98 67
54 42 37 61 83 49 45 35 42 43 34 54 97 40 75 73 107 84 77 70
79 106 56 52 59 79 85 84 65 51 49 70 67 63 80 70 69 44 34 60
55 70 55 43 58 35 49 43 41 49 50 37 47 41 40 41 47 39 49 41
56 60 32 47 44 59 55 58 69 60 61 56 55 41 59 63 63 59 44 36
67 61 54 66 46 29 32 60 67 36 54 50 42 45 42 43 42 68 89 68
41 57 40 31 36 38 35 45 42 42 66 43 44 72 80 62 56 67 57 61
85 80 112 103 62 54 55 38 120 87 66 64 43 62 44 50 51 91 81 46
53 135 84 88 83 81 89 89 75 76 61 67 59 92 102 140 133 137 83 83
61 66 66 97 98 84 74 93 80 95 80 72 94 92 114 120 127

BEV-J04B 197

208 250 257 250 196 178 128 128 95 148 129 125 95 106 123 131 112 108 114 66
53 38 34 77 84 55 39 33 40 46 31 53 102 44 69 80 100 88 73 71
78 104 54 52 59 77 87 86 62 52 50 67 72 58 74 71 63 46 40 58
52 67 51 52 56 41 47 31 53 46 43 45 47 32 49 39 43 51 38 42
58 40 45 53 44 52 59 65 69 49 54 49 63 42 57 63 58 59 42 42
66 57 55 70 45 28 43 58 61 45 58 38 49 42 45 39 42 73 82 73
35 47 36 39 34 41 36 46 36 45 59 36 45 69 84 58 62 68 56 61

81 81 112 100 53 54 58 46 105 85 64 67 47 50 41 59 51 87 83 52
56 124 84 90 76 87 99 84 82 74 80 59 61 92 121 120 143 132 81 87
56 66 68 93 102 81 78 89 75 96 82 68 99 91 109 121 124

BEV-J05A 46

329 314 374 432 349 268 238 138 175 209 294 268 282 210 191 274 243 295 239 218
221 249 194 234 255 249 229 200 218 312 246 362 380 328 398 347 319 455 415 353
387 289 268 140 142 154

BEV-J05B 46

325 322 366 446 339 296 260 130 180 214 268 273 253 204 188 278 253 298 251 210
225 251 193 236 255 255 232 197 221 307 251 359 383 330 406 340 319 484 416 368
410 284 268 145 151 128

BEV-J06A 61

502 592 492 413 415 433 229 235 304 362 290 236 350 149 163 192 228 277 284 242
287 97 68 34 69 86 103 85 102 144 156 130 205 283 259 242 215 298 124 111
86 167 162 150 169 184 160 262 225 242 311 350 165 234 130 107 190 267 287 302
286

BEV-J06B 61

515 586 495 409 418 446 239 205 277 469 286 234 350 158 155 204 225 281 280 254
281 101 54 41 80 81 104 84 102 151 183 133 212 320 213 249 225 293 124 108
79 173 157 158 156 190 165 246 249 245 328 348 179 241 140 107 177 245 274 299
292

BEV-J07A 84

213 294 302 380 282 324 402 388 459 516 362 263 149 134 200 217 217 250 279 289
285 211 188 276 246 298 324 169 159 86 187 231 296 240 292 343 220 206 176 325
314 90 72 87 107 112 168 182 124 130 121 164 163 162 168 188 190 191 219 236
83 57 58 72 87 83 70 96 67 62 117 138 125 95 132 87 82 103 128 151
87 88 67 84

BEV-J07B 84

221 289 309 375 307 332 433 398 430 530 358 271 146 139 194 222 215 251 276 297
278 215 188 272 247 300 335 161 161 90 173 246 300 247 286 339 221 200 190 325
311 85 76 87 114 110 165 188 125 133 121 165 162 164 171 193 207 212 196 234
85 59 54 77 90 76 78 90 61 67 111 142 121 99 131 82 79 114 124 145
90 95 63 74

BEV-J08A 112

302 435 294 353 270 313 264 283 306 302 134 43 44 42 102 80 80 98 134 179
212 144 199 235 125 125 114 114 127 152 149 138 119 80 82 95 125 136 191 161
173 191 188 199 159 133 167 202 190 156 146 203 290 258 231 275 253 227 169 193
162 188 188 202 227 187 157 186 199 163 168 234 145 172 135 174 127 119 149 189
167 170 120 64 60 118 138 87 83 72 93 132 111 133 130 120 106 91 207 154
143 120 152 133 142 168 156 172 169 276 213 202

BEV-J08B 112

300 428 302 352 267 303 268 282 306 303 134 41 43 46 103 84 78 94 130 179
214 139 205 252 128 119 112 108 118 163 151 134 115 85 76 100 124 135 185 158
170 186 188 191 155 124 167 198 194 148 146 204 286 273 227 272 253 232 169 193
160 186 192 198 221 195 158 188 202 175 169 235 143 171 135 165 125 127 167 176
167 169 116 67 58 122 136 89 88 63 96 128 112 132 134 118 108 94 204 158
149 102 142 141 145 152 162 173 162 259 221 192

BEV-J10A 48

180 109 98 141 220 162 194 217 104 81 173 560 652 461 321 222 207 178 124 194
209 310 223 213 176 179 210 207 181 197 152 170 207 200 197 178 216 170 189 171
149 110 125 159 169 152 150 136

BEV-J10B 48

171 91 95 141 215 173 200 215 112 80 162 513 649 503 364 208 221 183 129 208

231 311 239 220 161 171 212 208 187 206 155 164 199 191 187 180 223 169 193 177
139 129 120 165 156 174 162 144

BEV-J11A 50

332 372 379 280 241 279 403 143 144 373 349 254 243 273 398 400 413 269 334 260
302 294 263 283 260 334 363 311 251 209 219 132 93 102 221 128 130 150 213 186
272 446 362 163 119 171 220 241 184 130

BEV-J11B 50

330 363 371 281 252 259 446 143 152 393 360 257 222 227 395 408 437 262 343 214
261 296 245 251 252 319 353 302 251 205 217 119 103 107 230 134 122 163 192 197
281 465 394 156 131 170 209 260 176 123

BEV-J12A 150

86 80 75 68 75 125 159 76 32 54 89 86 94 138 126 124 76 61 70 117
129 170 157 94 118 67 109 102 130 167 129 66 59 125 123 135 144 111 130 117
67 39 119 94 73 86 41 32 43 54 69 32 43 32 53 29 37 70 52 50
60 73 72 92 49 40 29 42 62 70 40 43 43 46 78 91 83 76 56 52
44 59 80 62 95 86 69 39 63 70 63 130 90 91 69 91 53 64 41 59
72 72 54 86 54 46 47 68 56 80 75 57 51 61 88 96 133 87 56 34
37 44 82 92 55 86 65 75 60 60 63 84 102 45 76 152 88 96 111 102
58 68 86 46 56 52 44 66 67 93

BEV-J12B 150

82 90 64 75 66 127 170 70 27 55 80 94 100 146 129 125 82 55 72 113
136 169 159 92 120 63 108 107 132 164 126 71 64 118 121 137 148 99 134 118
53 45 116 96 70 85 44 32 39 58 72 35 46 32 42 35 41 69 41 52
60 67 75 91 44 44 33 41 57 69 45 40 46 53 76 86 75 79 63 41
55 57 71 72 86 85 69 45 67 69 62 128 78 90 73 108 57 56 51 45
71 74 55 97 53 53 42 71 67 71 72 61 47 63 85 112 134 99 38 42
38 48 68 87 57 92 68 67 63 64 62 77 92 48 74 168 84 98 91 91
74 97 84 52 51 49 43 65 65 90

BEV-J13A 146

129 289 141 55 93 139 155 146 192 159 171 101 82 100 127 164 239 247 164 168
129 170 122 127 163 121 50 46 111 101 122 124 68 83 57 43 44 80 94 80
71 53 30 34 45 61 43 47 41 75 35 37 82 77 85 76 63 62 82 70
42 40 80 77 69 47 35 38 50 78 64 64 62 40 37 32 41 40 53 46
56 66 36 58 40 40 44 37 47 42 46 44 28 33 41 49 50 34 73 63
39 35 60 47 57 44 43 45 62 75 73 73 68 44 45 48 27 33 36 43
60 42 37 35 34 40 46 61 35 38 60 57 49 53 51 48 39 39 34 40
37 53 45 54 69 59

BEV-J13B 146

136 271 134 68 88 134 142 199 165 146 156 79 81 105 130 165 231 247 161 161
116 164 122 122 159 106 49 51 103 97 119 113 71 67 55 44 42 76 94 72
71 43 29 43 38 57 42 48 44 68 34 34 82 70 91 73 66 54 76 61
52 37 57 65 54 46 32 42 45 77 60 55 67 38 35 35 38 41 53 45
53 52 47 50 42 34 46 40 42 37 44 40 58 40 38 48 40 25 73 56
41 31 50 44 50 40 45 43 50 73 76 71 66 55 37 42 31 38 36 42
50 45 36 35 41 32 41 62 38 29 56 50 53 40 48 44 50 37 31 40
38 47 48 57 60 55

BEV-J14A 89

154 172 149 117 135 188 158 152 159 191 142 109 120 106 128 129 127 162 118 99
113 110 130 97 94 76 115 83 109 133 109 103 120 150 145 85 106 62 90 94
114 115 95 114 54 58 128 101 84 105 112 74 83 83 66 99 46 65 107 75
71 53 47 109 61 51 52 63 55 57 63 50 52 46 48 93 63 65 54 65
83 91 103 86 76 56 63 71 89

BEV-J14B 89

163 155 150 127 134 190 153 149 165 190 134 114 121 100 130 133 126 154 118 104
111 112 131 97 96 71 113 81 106 139 97 111 119 145 138 83 101 65 92 96
111 121 93 105 63 57 128 97 86 106 112 65 92 79 77 87 39 78 104 81
66 62 53 103 75 55 52 67 56 66 43 56 60 45 56 87 82 49 61 58
79 94 99 88 77 45 65 56 71

BEV-J15A 55

144 91 73 47 71 50 101 116 91 177 181 179 316 272 370 358 319 307 295 307
249 176 164 146 135 169 227 199 222 276 277 215 297 382 192 170 204 240 216 234
188 146 149 181 147 163 155 123 126 171 224 204 190 186 235

BEV-J15B 55

84 85 79 46 76 50 110 117 93 177 198 179 325 269 370 359 317 306 300 309
247 176 167 146 141 173 225 198 222 279 290 215 308 375 179 166 193 235 211 255
201 142 151 179 145 159 133 129 129 184 203 210 188 190 207

BEV-J16A 56

118 109 100 72 80 77 128 227 255 49 53 66 71 49 112 160 195 168 119 99
129 130 180 240 118 80 90 96 82 129 140 186 151 125 106 202 182 79 143 86
79 86 98 115 121 138 110 103 91 31 65 38 56 59 68 67

BEV-J16B 56

133 114 95 81 73 85 128 231 248 60 53 59 76 55 111 157 192 172 110 105
134 122 181 242 119 78 90 93 83 124 146 188 149 125 95 201 187 78 140 85
80 84 106 118 116 139 106 103 94 28 66 36 54 70 57 67

BEV-J18A 74

376 389 243 412 402 263 254 301 285 274 115 120 157 324 259 386 257 182 185 312
437 292 178 311 229 164 191 118 62 59 89 139 152 317 273 191 274 205 420 243
158 167 196 185 161 240 192 232 181 191 187 280 163 199 164 141 198 144 216 196
178 263 129 308 172 234 187 214 216 204 110 173 193 207

BEV-J18B 74

329 427 244 416 410 278 263 311 286 281 102 124 169 317 258 353 297 188 179 317
436 291 180 306 212 166 185 111 54 51 95 143 150 332 273 211 280 203 447 254
160 165 190 189 160 240 203 246 177 201 195 272 162 207 173 141 192 146 219 200
175 281 116 319 166 226 189 200 226 198 125 178 193 201

BEV-J19A 73

270 227 171 403 418 440 345 299 287 315 165 285 226 334 298 249 301 143 236 194
198 252 331 258 288 111 93 63 110 149 141 134 145 181 200 166 231 286 278 309
267 335 126 79 84 206 221 209 202 221 208 381 384 415 468 456 171 148 158 167
213 238 257 264 318 185 182 211 146 140 87 85 107

BEV-J19B 73

249 225 171 400 434 434 338 299 285 325 147 278 261 317 295 244 321 142 231 185
194 252 326 264 282 113 94 63 108 148 130 139 149 183 195 181 223 264 277 311
267 330 143 88 75 207 236 212 208 228 225 379 398 421 452 459 173 148 184 146
199 226 261 263 324 191 185 209 140 139 82 92 69

BEV-J20A 47

262 378 594 459 731 849 363 294 272 260 297 373 165 218 199 336 310 305 244 270
292 332 303 281 161 107 112 101 281 334 345 275 301 233 219 304 234 175 116 111
218 253 211 181 213 282 247

BEV-J20B 47

260 407 606 458 897 854 367 287 277 257 309 380 166 220 201 338 312 304 239 280
291 318 312 320 161 109 110 108 281 340 351 281 268 230 197 304 233 176 111 107
214 254 208 179 213 280 226

BEV-J21A 48

183 229 441 326 294 263 350 517 426 478 433 309 246 442 359 328 399 348 342 339
445 398 298 267 204 210 337 382 383 186 147 140 129 238 273 165 125 144 226 177
216 178 122 137 126 117 90 86

BEV-J21B 48

198 218 442 330 278 267 350 516 416 488 439 310 248 439 361 329 399 355 347 328
442 369 274 284 206 231 326 369 377 181 151 134 132 237 274 156 130 153 228 177
216 197 121 141 120 122 97 76

BEV-J24A 63

292 190 161 90 67 68 94 144 231 258 144 95 264 152 220 338 387 424 444 138
99 123 194 320 241 133 96 71 82 115 186 206 277 257 174 140 231 199 154 213
91 104 137 164 177 169 148 188 122 113 83 98 70 86 95 104 91 182 145 193
101 113 96

BEV-J24B 63

270 205 160 96 64 65 96 141 235 262 144 97 281 183 190 325 370 429 415 138
96 119 199 360 242 127 101 69 82 108 194 202 277 261 173 136 236 195 153 227
91 103 137 160 177 171 148 179 126 116 80 100 73 84 94 104 90 182 147 197
108 103 81

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings;

about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.



Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976



Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil



Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis



Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. Measuring Ring Widths. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Figure A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date

an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. Estimating the Felling Date. As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has

sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where ‘associated groups of fellings’ are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is ‘pushed back in time’ as far as the age of samples will allow. This process is illustrated in Figure A6. We have a

master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

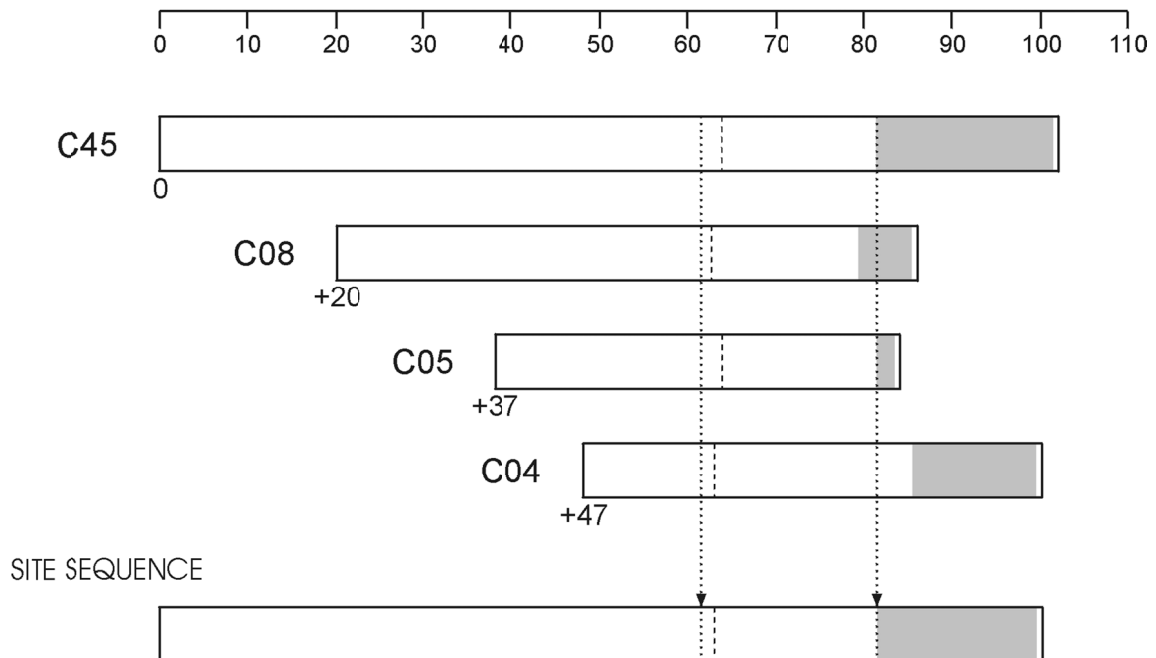


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

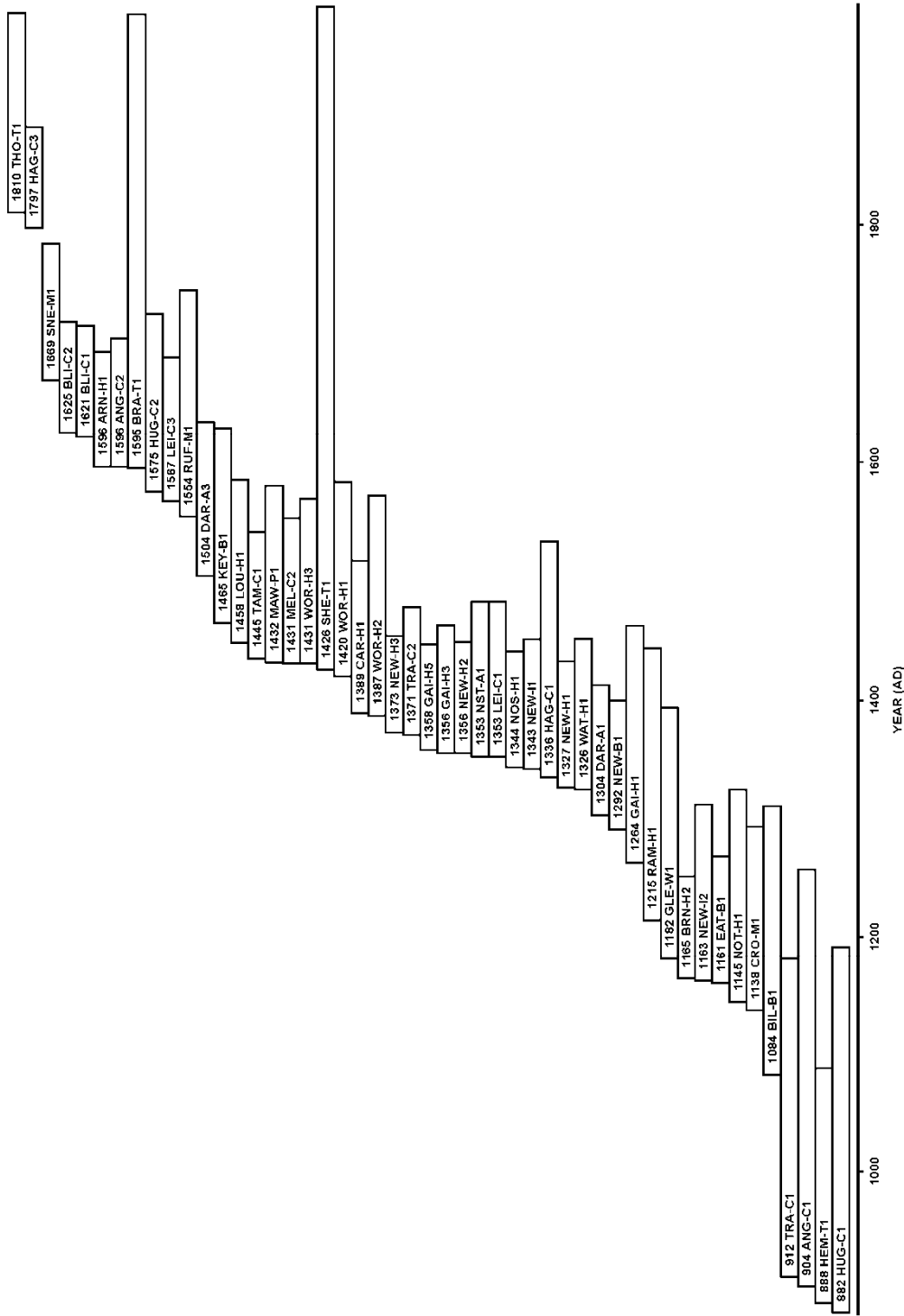
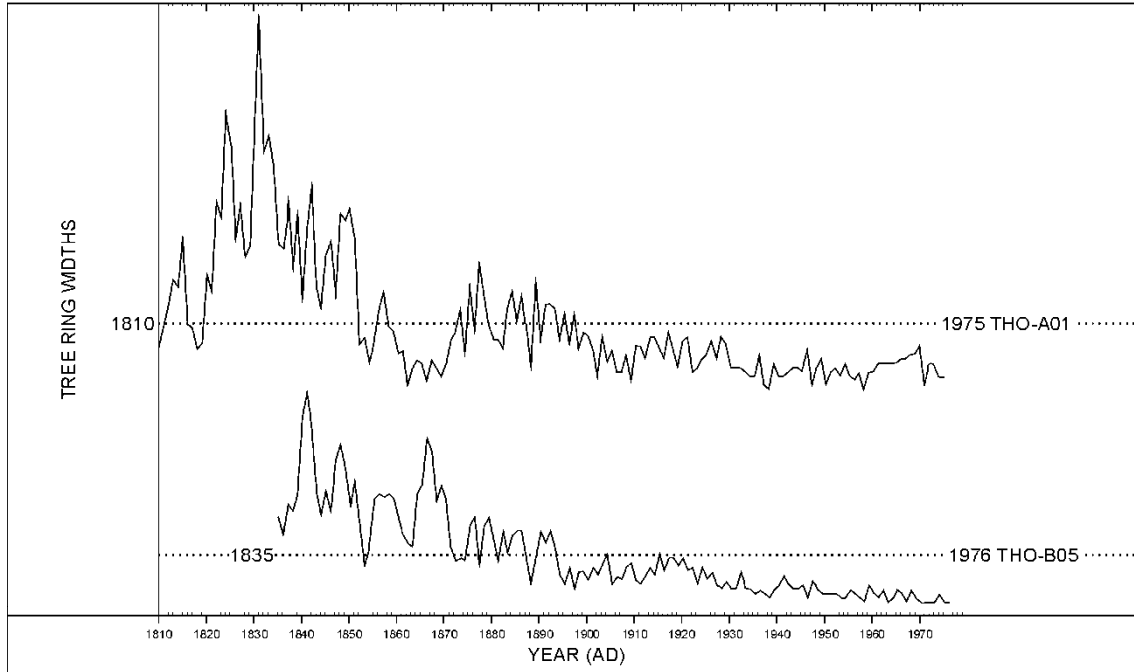


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

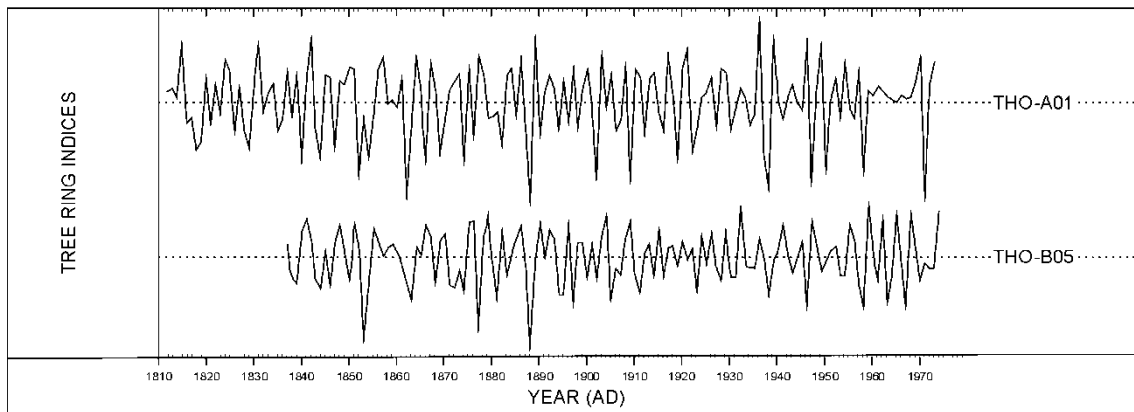


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths
The growth trends have been removed completely

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